

Reducing Air Pollution Exposure in Passenger Vehicles and School Buses

Contract Number: 11-310

**Dr. Yifang Zhu
Associate Professor
(Principal Investigator)**

Department of Environmental Health Sciences, Fielding School of Public Health

University of California, Los Angeles

Disclaimer

The statements and conclusions are those of the authors and not necessarily those of California Air Resources Board and National Science Foundation.

The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

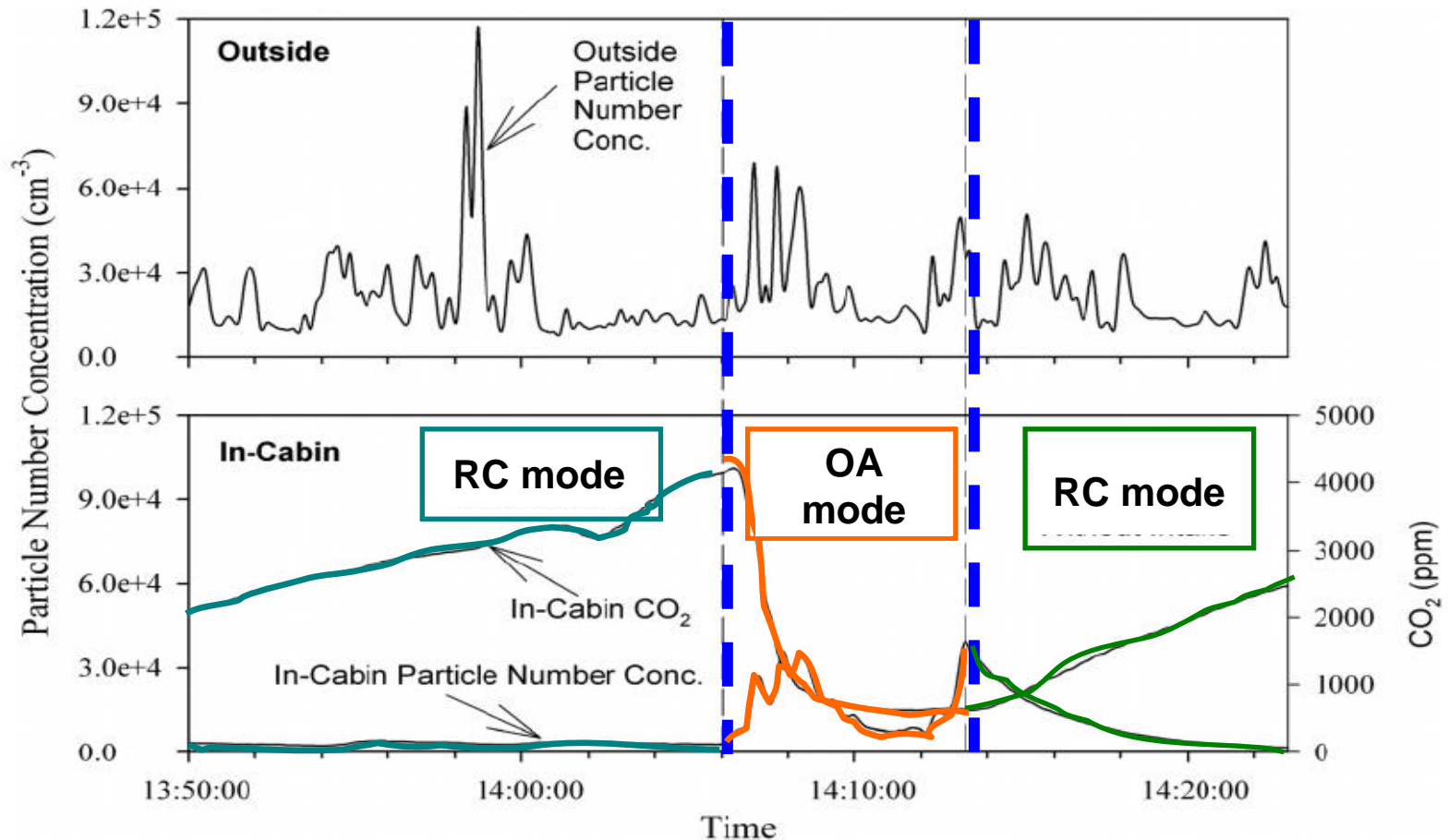
Background & Motivation

- High levels of Ultrafine Particles (UFP, diameter < 100 nm) were observed on roadways. (Zhu et al., 2007)
- On-road concentration is one or two orders of magnitude higher ($> 10^5$ #/cm³) than the urban background ($10^3 \sim 10^4$ #/cm³). (Morawska et al., 2008)
- Short commuting time represents a large fraction of daily UFP exposures. (Fruin et al., 2008)
- In-cabin exposure to UFPs is high, because of...
 - Close proximity to emission sources
 - Leaky vehicle envelope
 - Low filtration efficiency for passenger cars
 - No effective filtration system for school buses

Background & Motivation

Key Point

Recirculation (RC) mode provides the best protection for UFP exposures, but passengers' exhalation leads to high CO_2 levels.

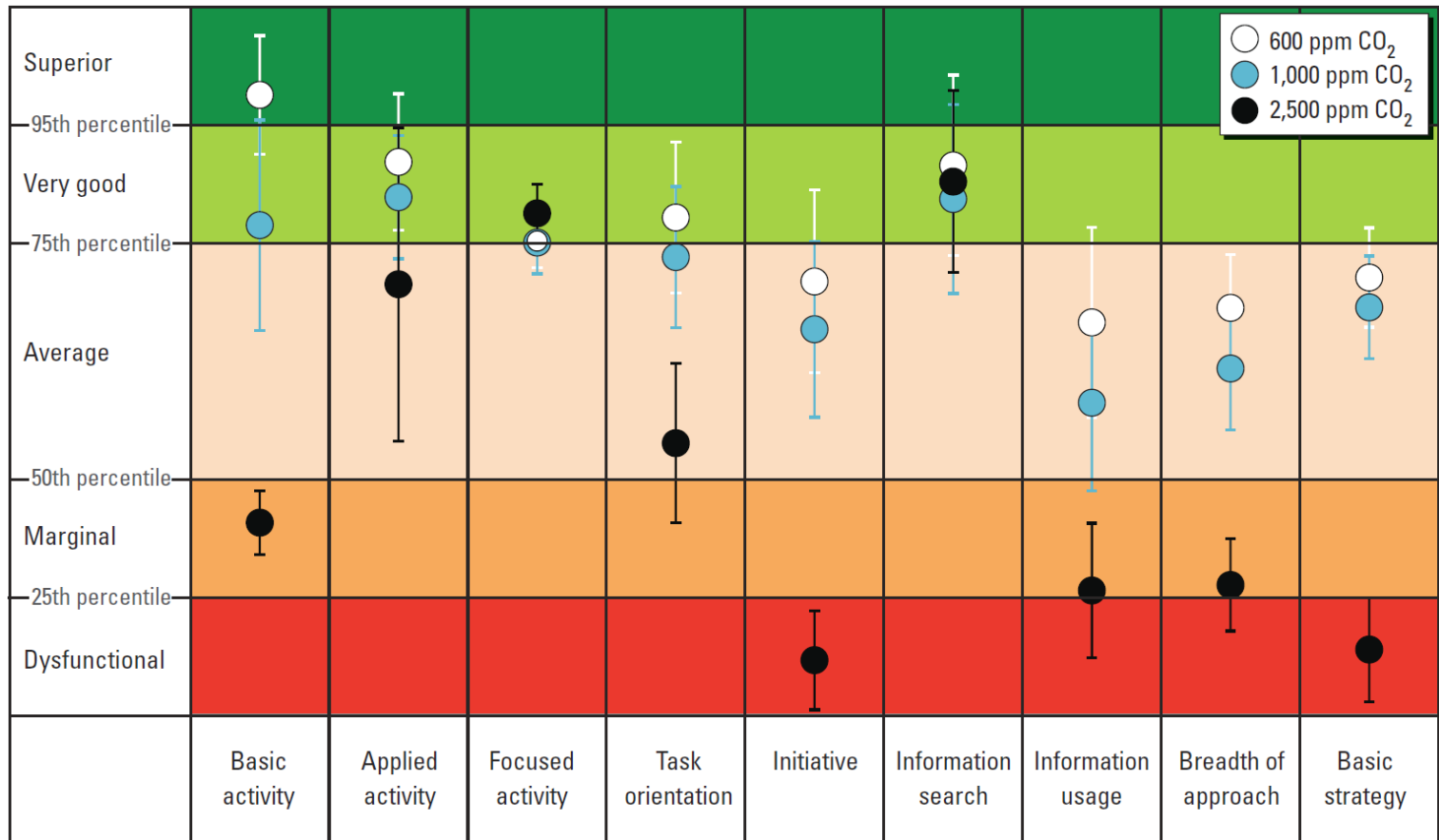


CO₂ Accumulation in Passenger Cars

On-road level: 500 ~ 600 ppm (freeways)

In-cabin level: **above 2500 ppm** with 2 passengers only **in 15 minutes**

Decision Making Performance Changes (Satish et al., 2012)



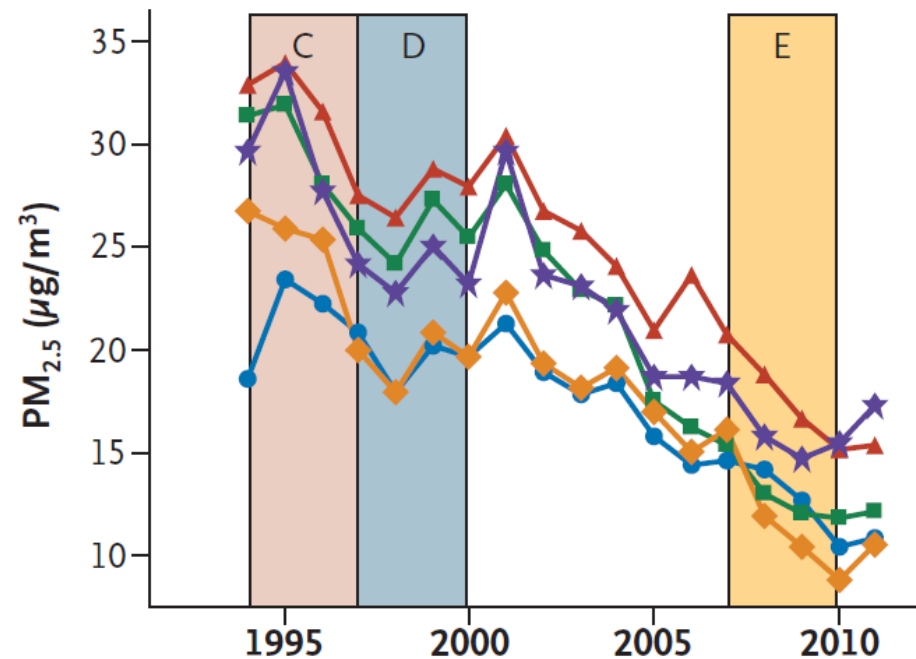
Children's Exposure and Health

- Immature respiratory systems
- Greater breathing rate per bodyweight
- Larger minute ventilation relative to lung size
- Greater fractional deposition with each breath

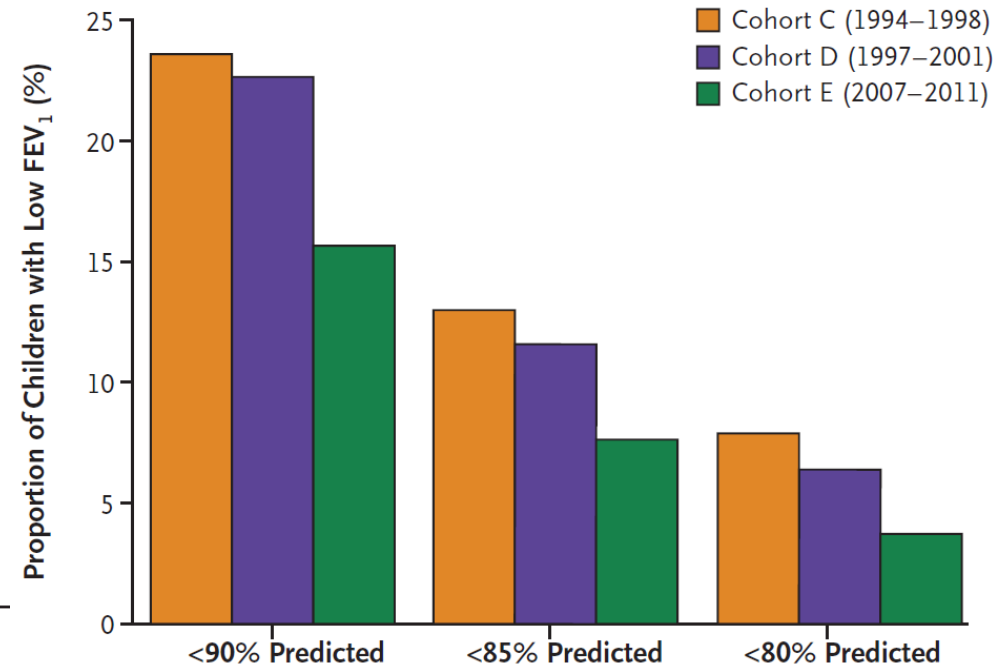


Better Air Quality & Improved Children's Lung Function

Ambient PM_{2.5} level



Improved Children's Lung Function



(FEV₁: Forced Expiratory Volume in 1 second)

Exposure in School Buses

- Children are exposed to high levels of air pollution from **self-pollution** and other **road traffic emissions** while riding school buses.

(Behrentz et al., 2004; Rim et al., 2008; Ireson et al., 2011)

- Diesel Oxidation Catalyst (DOC) and Crankcase Filtration System (CFS) help to reduce tail-pipe emissions, **not necessarily to improve in-cabin air** quality. (Zhang and Zhu, 2011)

- In the U.S., about **25 million** children are carried by **600,000** school buses to and from school each day, and a typical child may ride a school bus **180 days** a year for a decade. (Marshall and Behrentz, 2005)



Project Objectives

Phase 1. Passenger Vehicles: High Efficiency Cabin Air (HECA) filter

- To determine to what extent an in-cabin HECA filter can reduce particle levels inside passenger vehicles
- To identify important factors affecting HECA filter's performance inside passenger vehicles

Phase 2. School Buses: On-board HECA filtration system

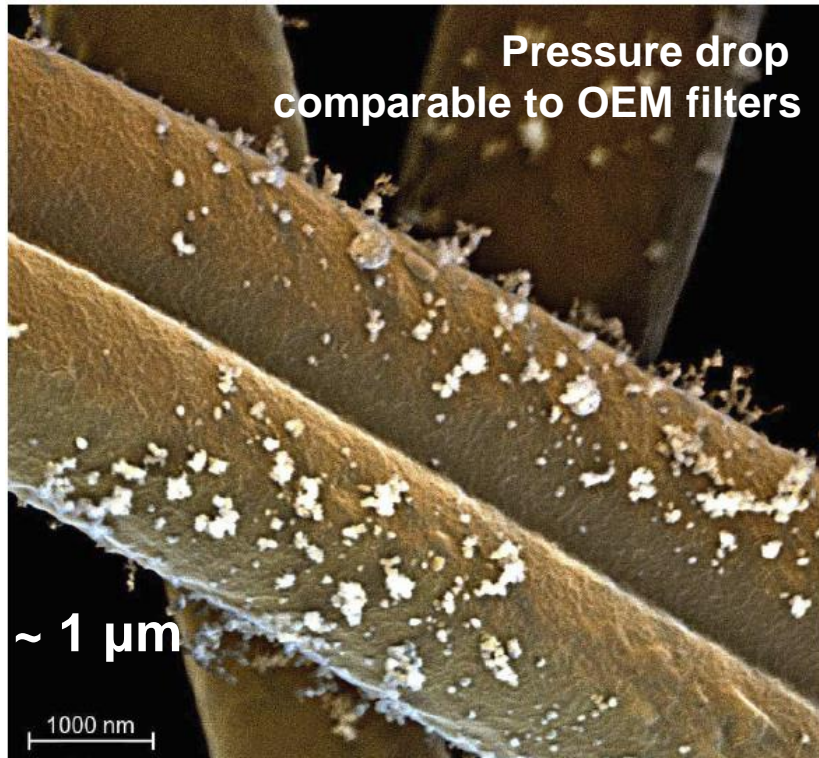
- To determine to what extent operating an on-board HECA filtration system can reduce particle levels inside school buses
- To identify important factors affecting the on-board HECA filtration system inside school buses

Phase I

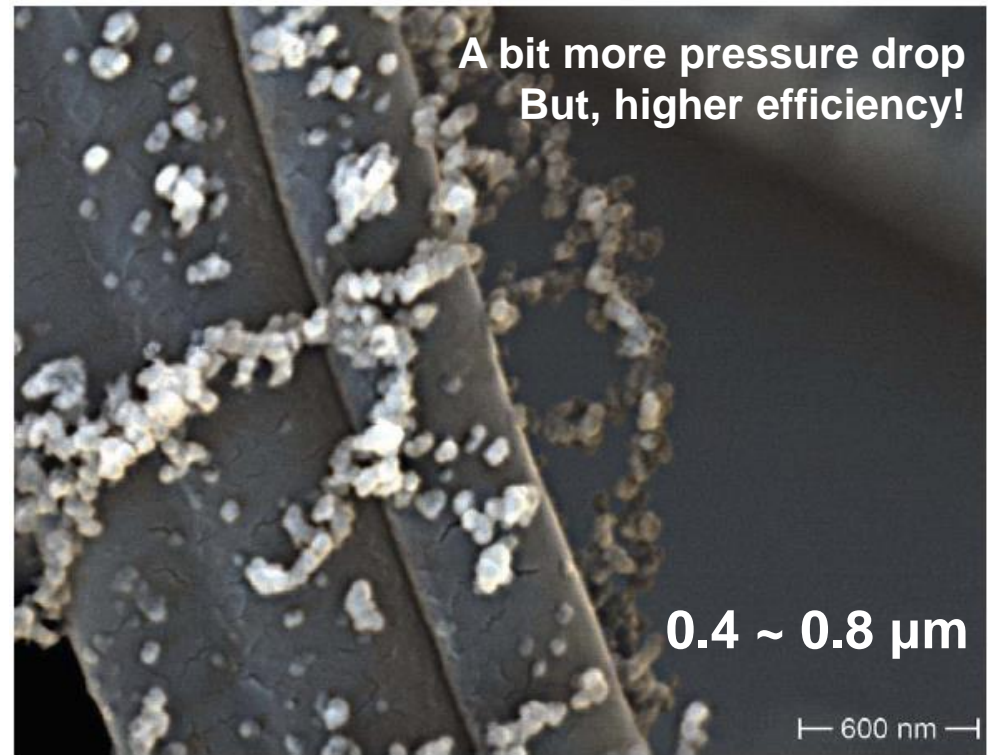
High Efficiency Cabin Air (HECA) Filtration for Passenger Vehicles

Development of HECA filters

HECA A Filter



HECA B Filter



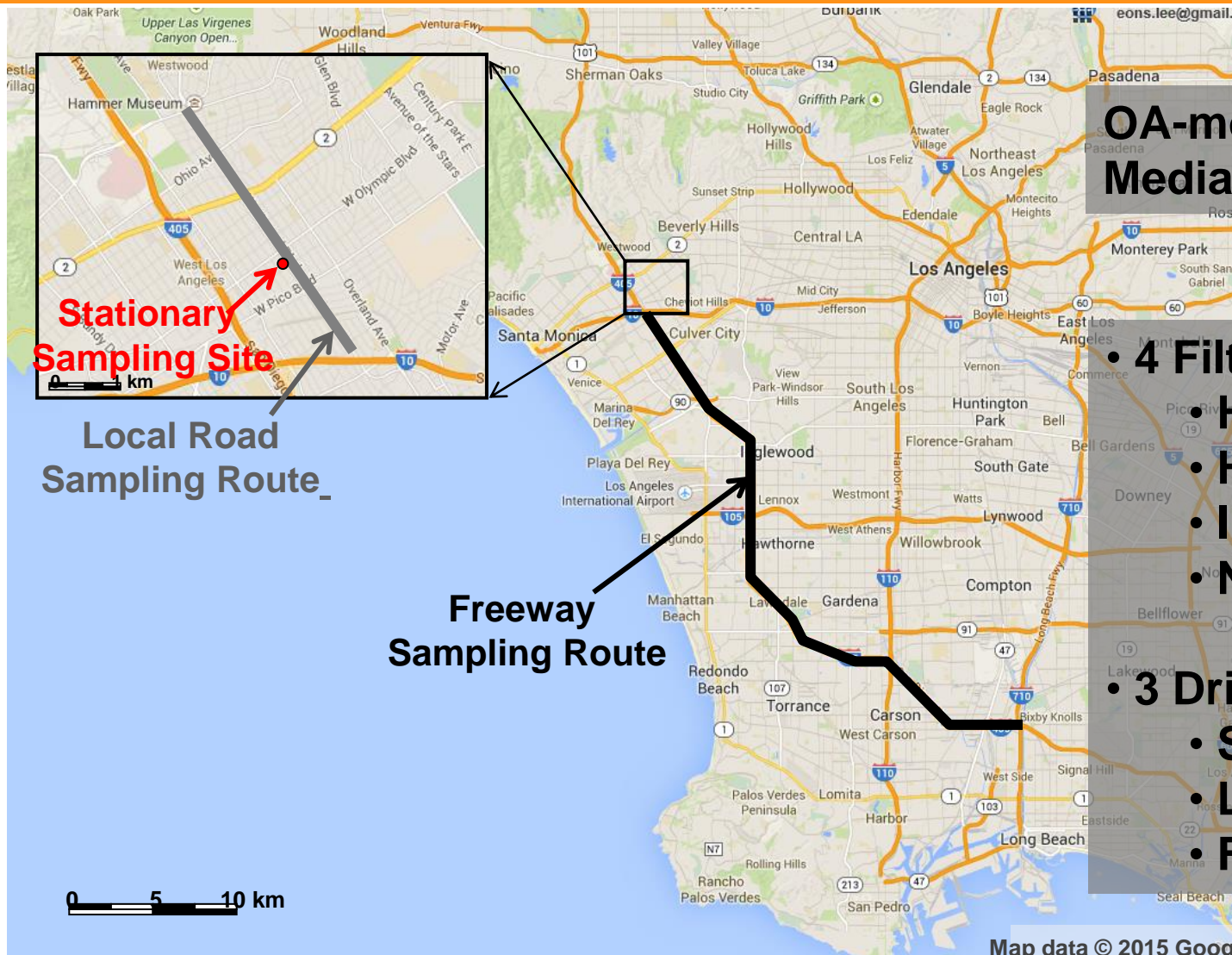
Both prototype filters have particle removal efficiency much higher than OEM filters. The difference is in the filter **fiber diameter**.

Experimental Set-up

- Less than 3 years
- California Vehicle Fleet

| Vehicle Type | Maker | Model | Year | Mileage (km) | Cabin Filter Locations | Cabin Volume (m ³) |
|--------------|------------|------------|------|--------------|------------------------|--------------------------------|
| Hatch-back | Ford | Focus | 2012 | 51,347 | Glove Box | 2.94 |
| | Toyota | Prius | 2012 | 9,102 | Glove Box | 3.88 |
| Sedan | Chevrolet | Impala | 2012 | 1,339 | Glove Box | 4.01 |
| | Honda | Accord | 2011 | 51,194 | Glove Box | 3.83 |
| | Hyundai | Sonata | 2013 | 21,712 | Glove Box | 3.41 |
| | Nissan | Sentra | 2012 | 30,398 | Under Dash | 3.50 |
| | Toyota | Camry | 2012 | 1,931 | Glove Box | 3.78 |
| | Volkswagen | Jetta | 2012 | 14,917 | Under Hood | 3.55 |
| SUV | Ford | Explorer | 2013 | 16,510 | Glove Box | 4.89 |
| | Toyota | Highlander | 2012 | 10,611 | Glove Box | 4.43 |
| Minivan | Honda | Odyssey | 2010 | 38,622 | Glove Box | 7.03 |
| | Toyota | Sienna | 2011 | 74,174 | Glove Box | 5.76 |

Testing Routes



OA-mode & Median Fan Setting

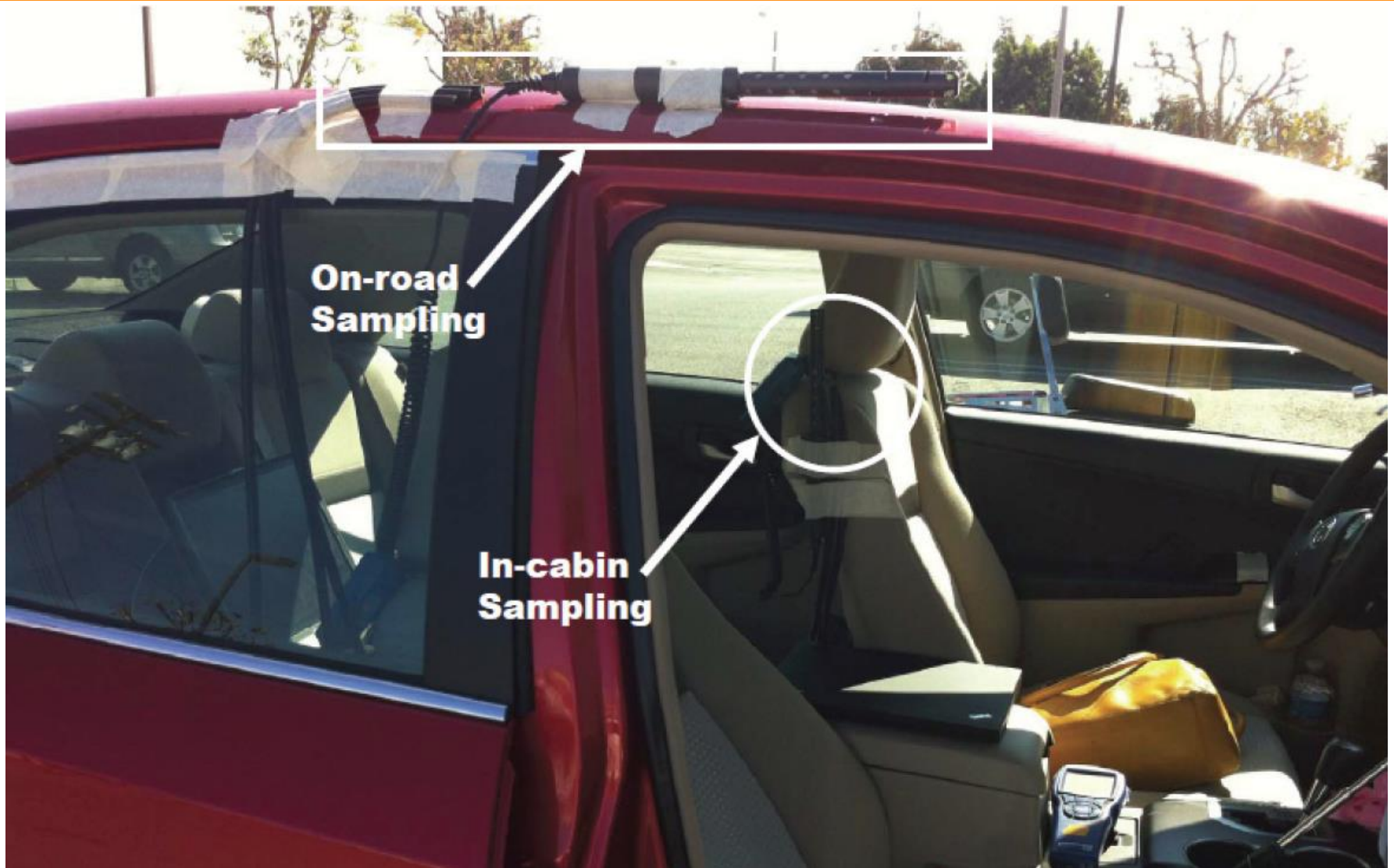
• 4 Filtration Scenarios

- HEPA B
- HEPA A
- In-use OEM
- No Filter

• 3 Driving Conditions

- Stationary
- Local
- Freeway

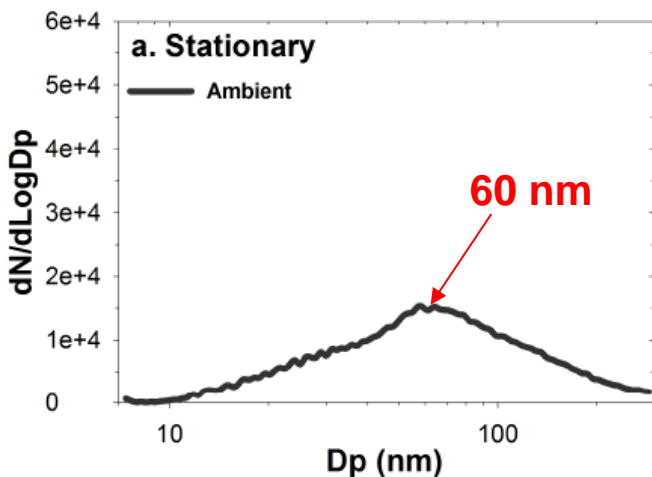
Instrument Set-up



Source Particle Size Distributions

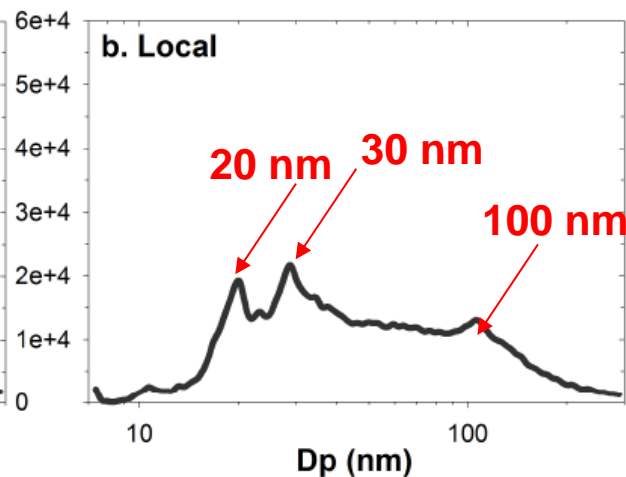
Particle Size Distributions in Different Experimental Conditions

Stationary



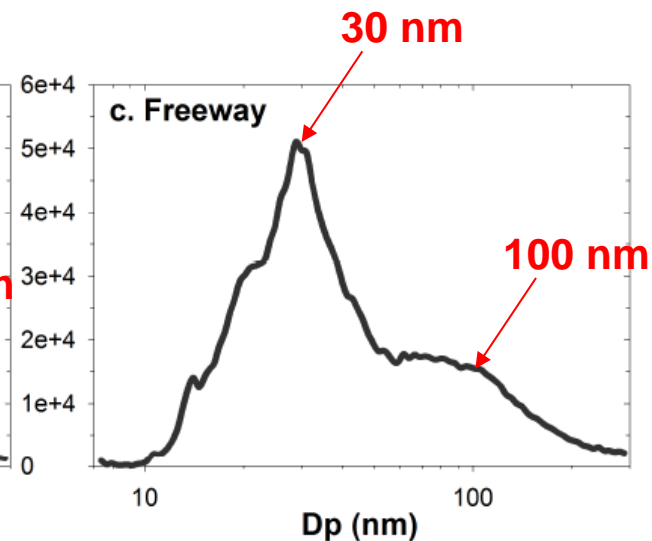
Larger particles

Local



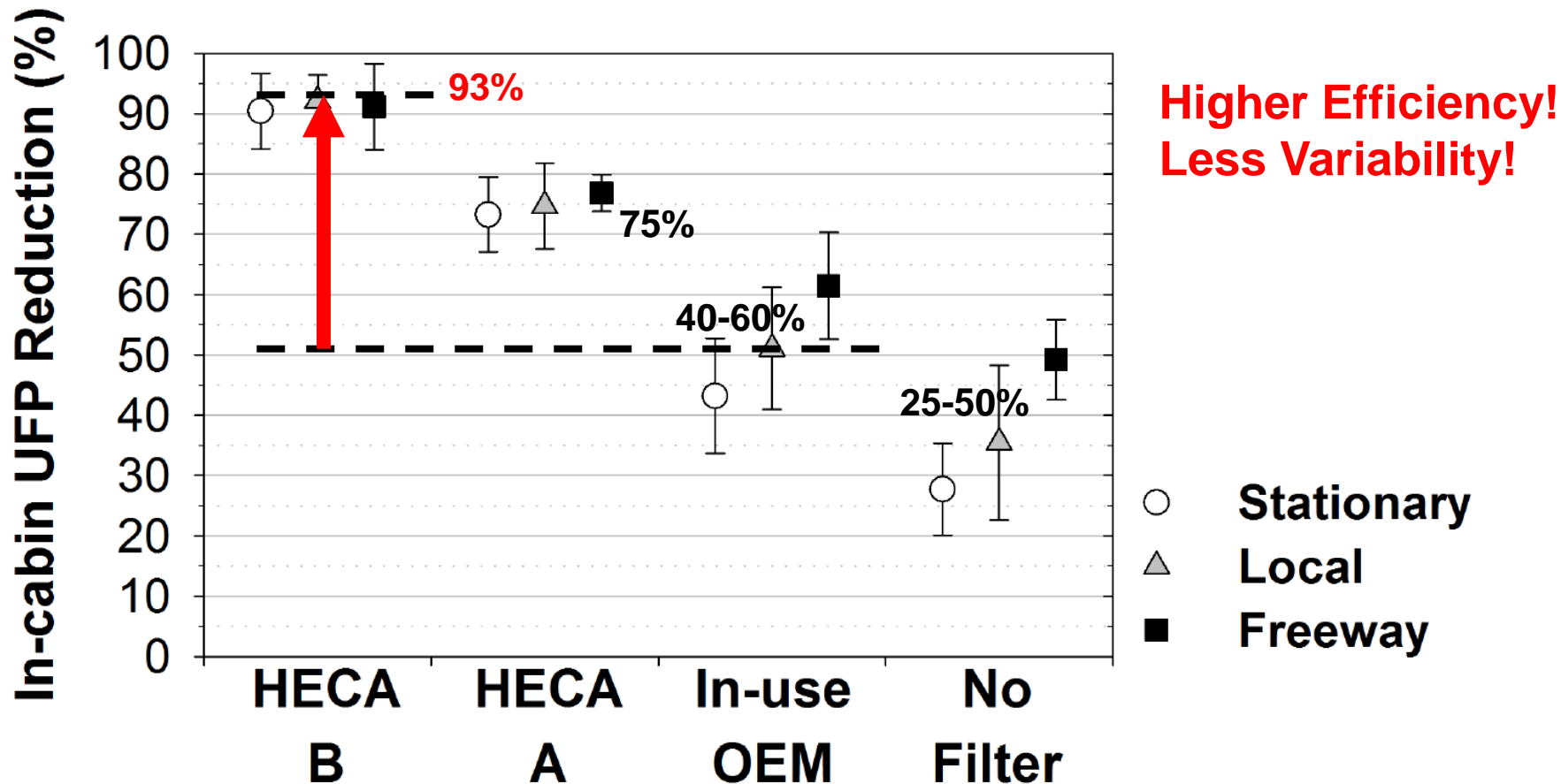
Complex size distribution

Freeway



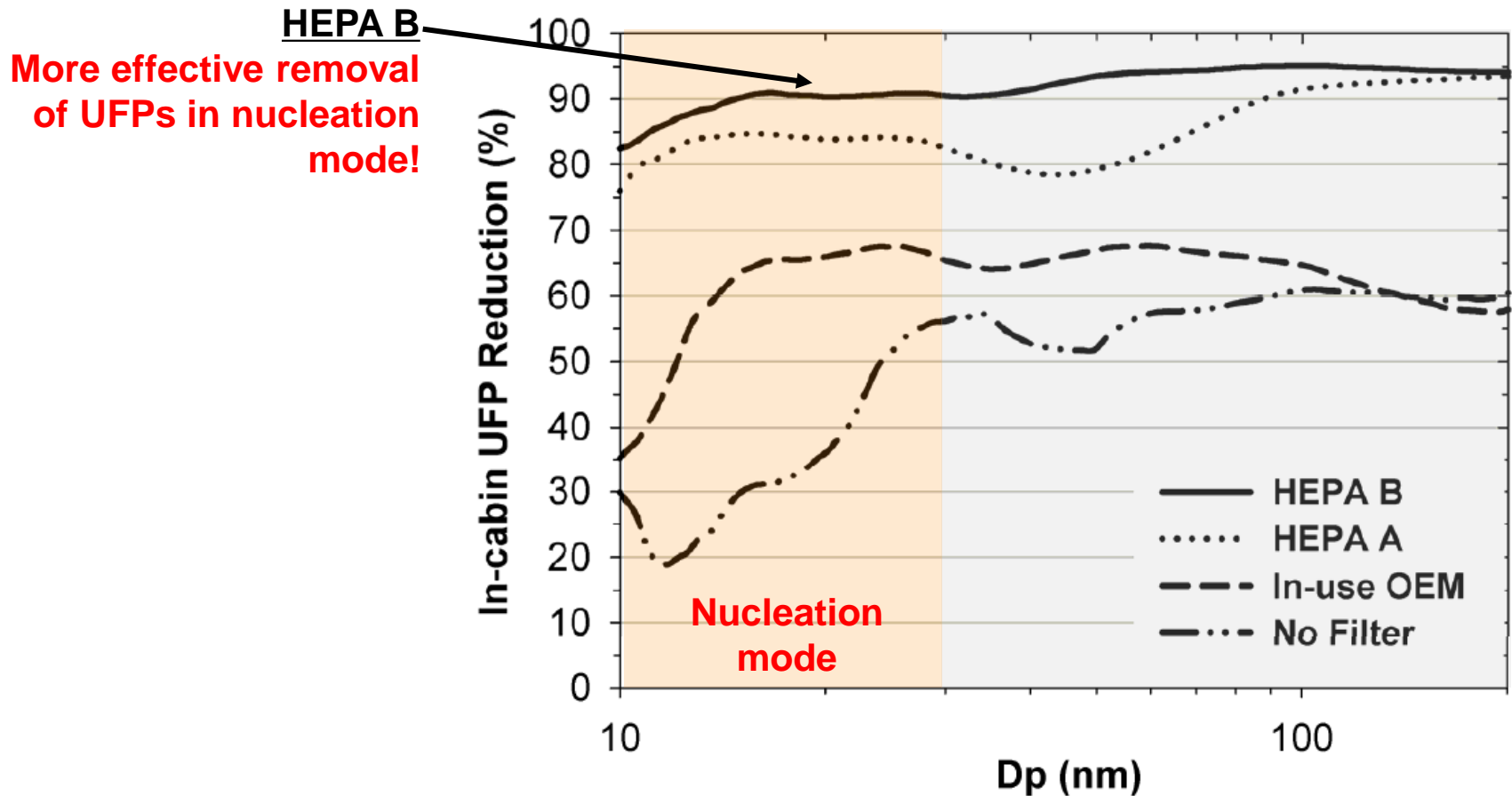
Dominant Nucleation mode particles
→ high diffusion

In-cabin UFP Reduction

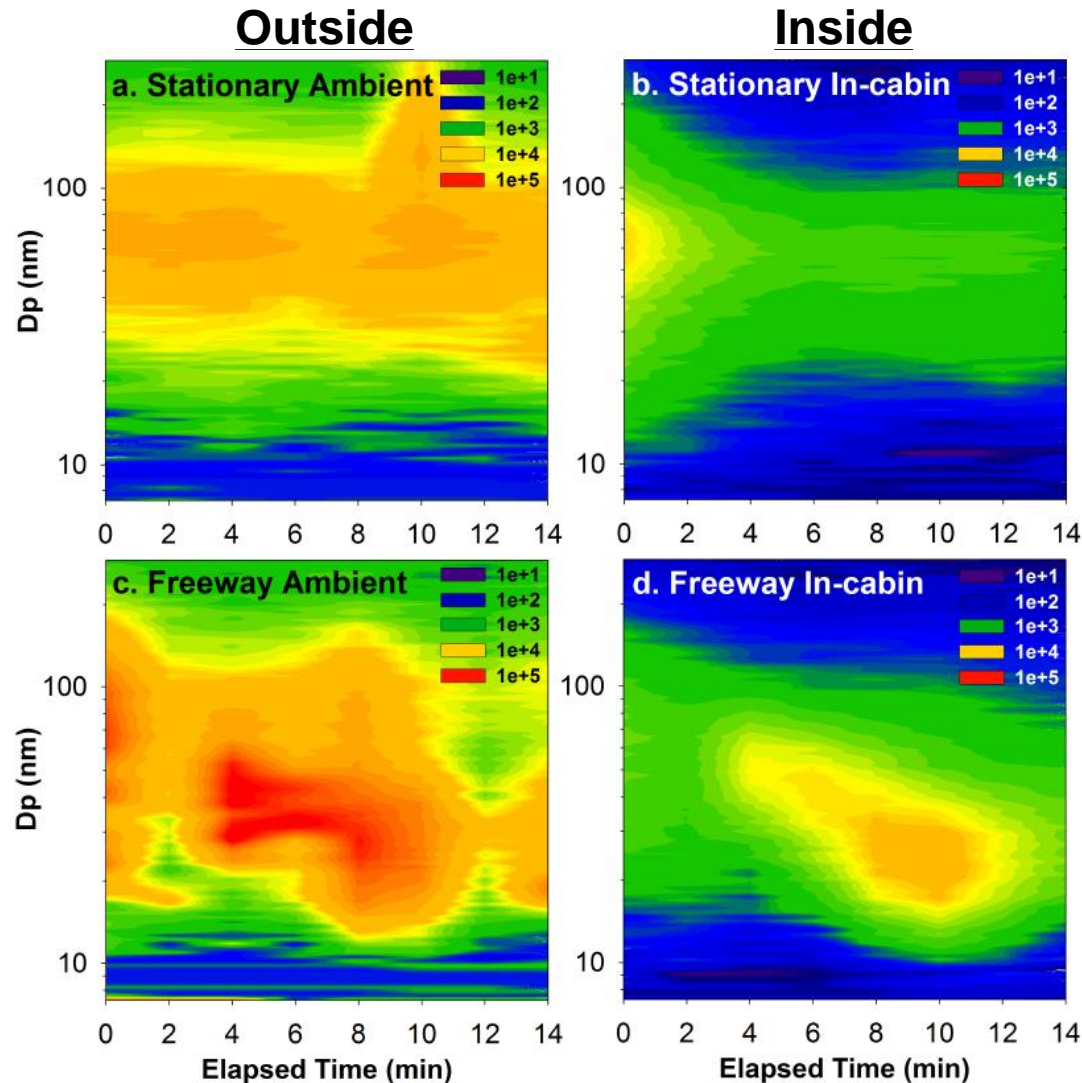


For each driving condition, HECA B and A filters provided significant in-cabin UFP reductions ($p < 0.001$) in comparison to OEM or no filter scenarios.

Size-resolved Particle Removal Efficiency



Temporal Changes of In-cabin UFPs



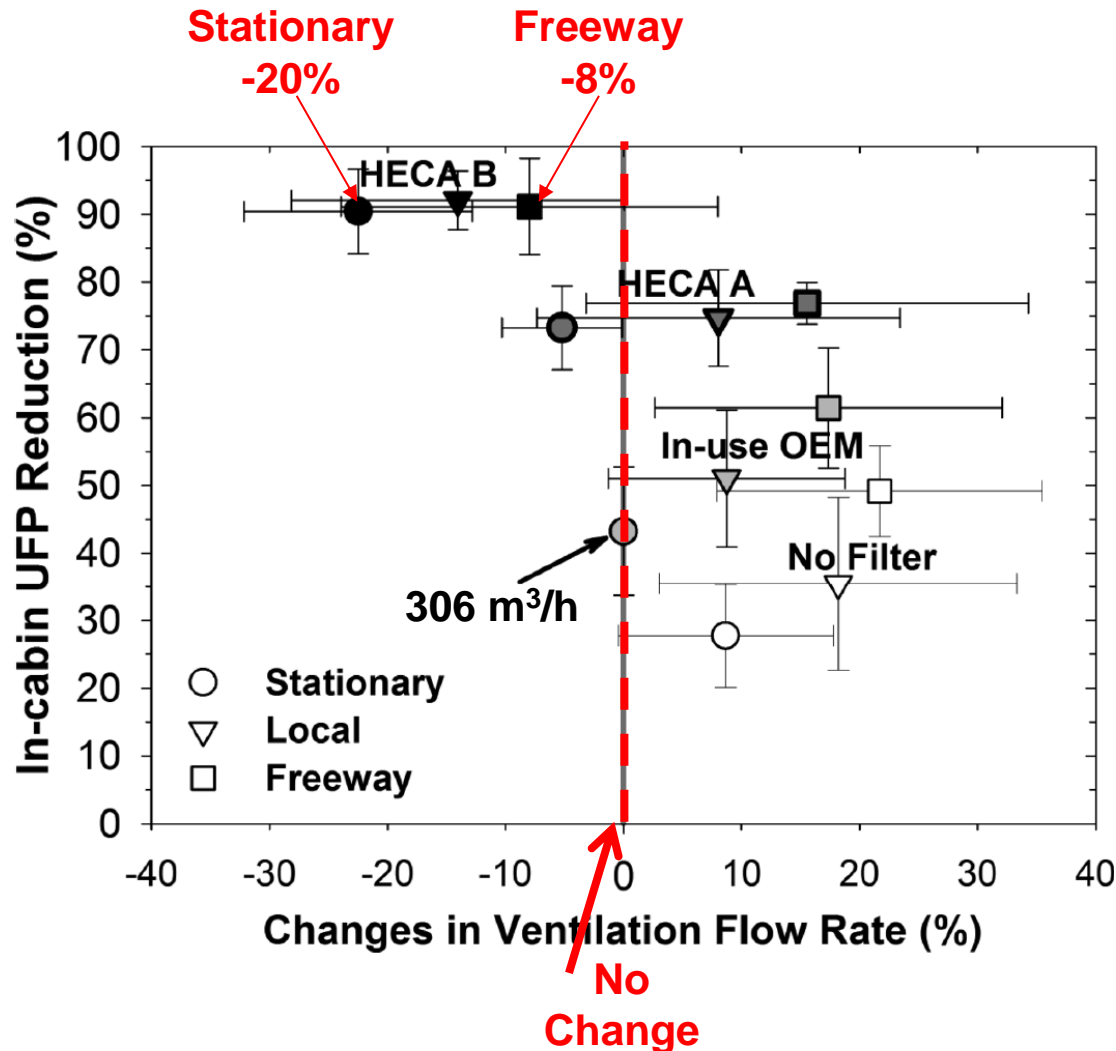
Stationary Condition

Substantially decreased
UFP number concentration

Freeway Condition

UFP was reduced by
an order of magnitude

Changes in Ventilation Air Flow Rate



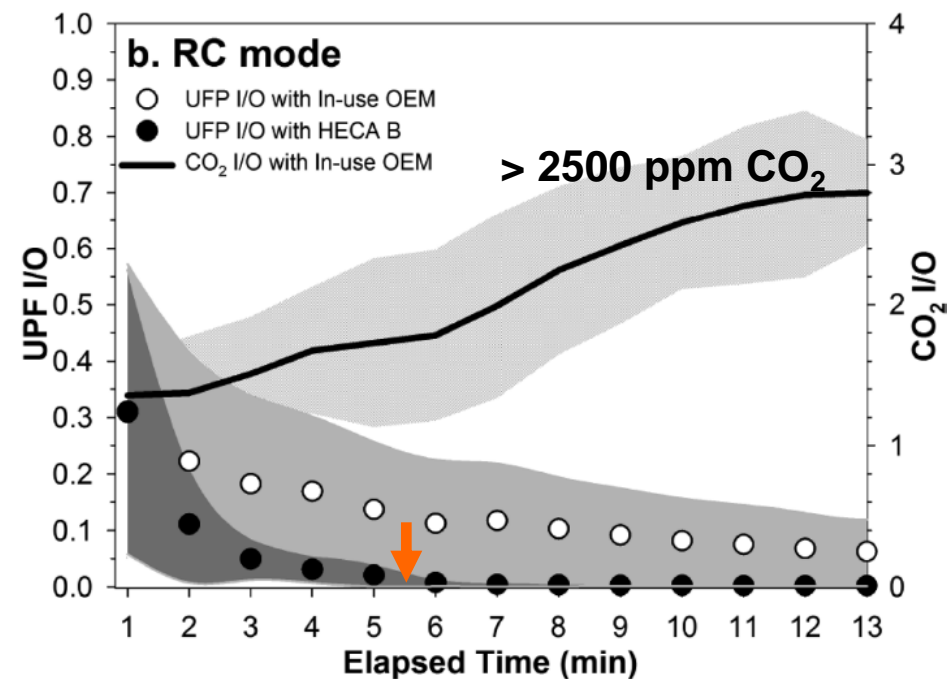
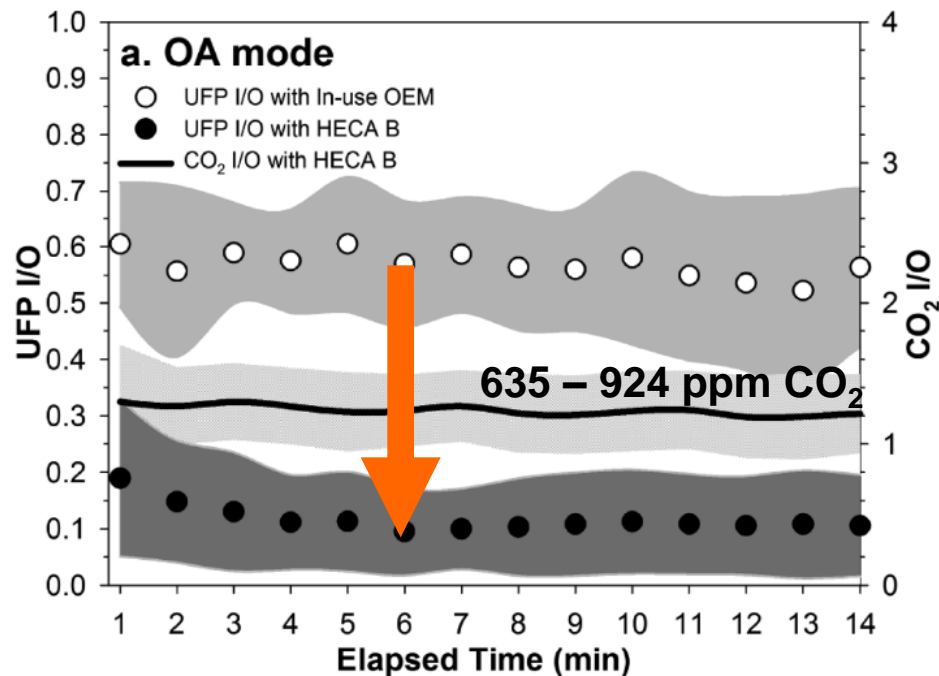
Pressure drop is present but would unlikely become a problem.

On Freeway,
Air-flow reduction is Less than 10%!

Black arrow indicates the averaged ventilation airflow rate of 12 vehicle models at the median fan setting (306 m³/h).

Simultaneous Control for UFPs & CO₂

Means & Standard Deviations
of measurement data from 12 passenger vehicles



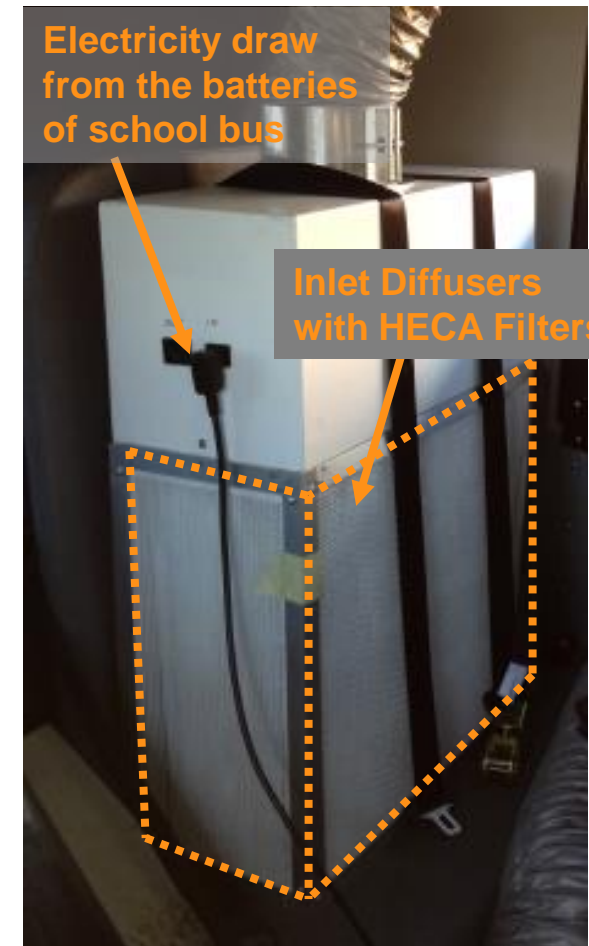
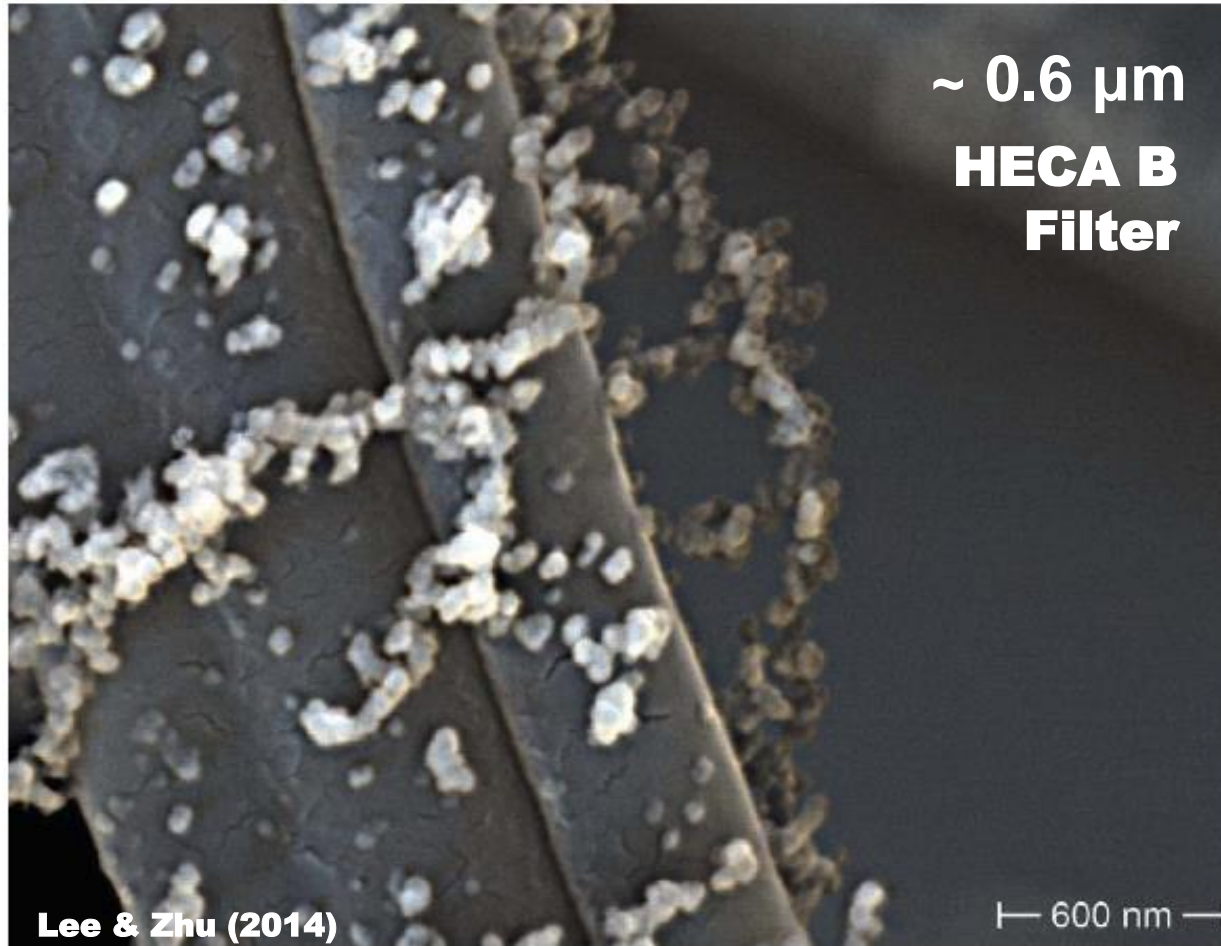
Phase 1. Summary

- Achieved a **simultaneous control** of UFPs and CO₂ using in-cabin HECA filters.
- **Approximately 93% reduction** of in-cabin UFPs on average in the field.
- **Thermal comfort issue would not likely be a problem** from ventilation air-flow reduction ~ 20 % in stationary conditions, < 10 % on freeway.
- **More effective UFP reduction in freeway** environments because nucleation mode particles were effectively removed by diffusion and interception.
- This control method holds in-cabin CO₂ build-up at **635-924 ppm** (vs. 2500 – 4000 ppm in RC mode) with 2 passengers.

Phase 2

On-board HECA Filtration System for School Buses

On-board HECA Filtration System



On-board HECA Filtration System

Jet Diffusers



Air Distribution Ducts



Small



Medium



Large



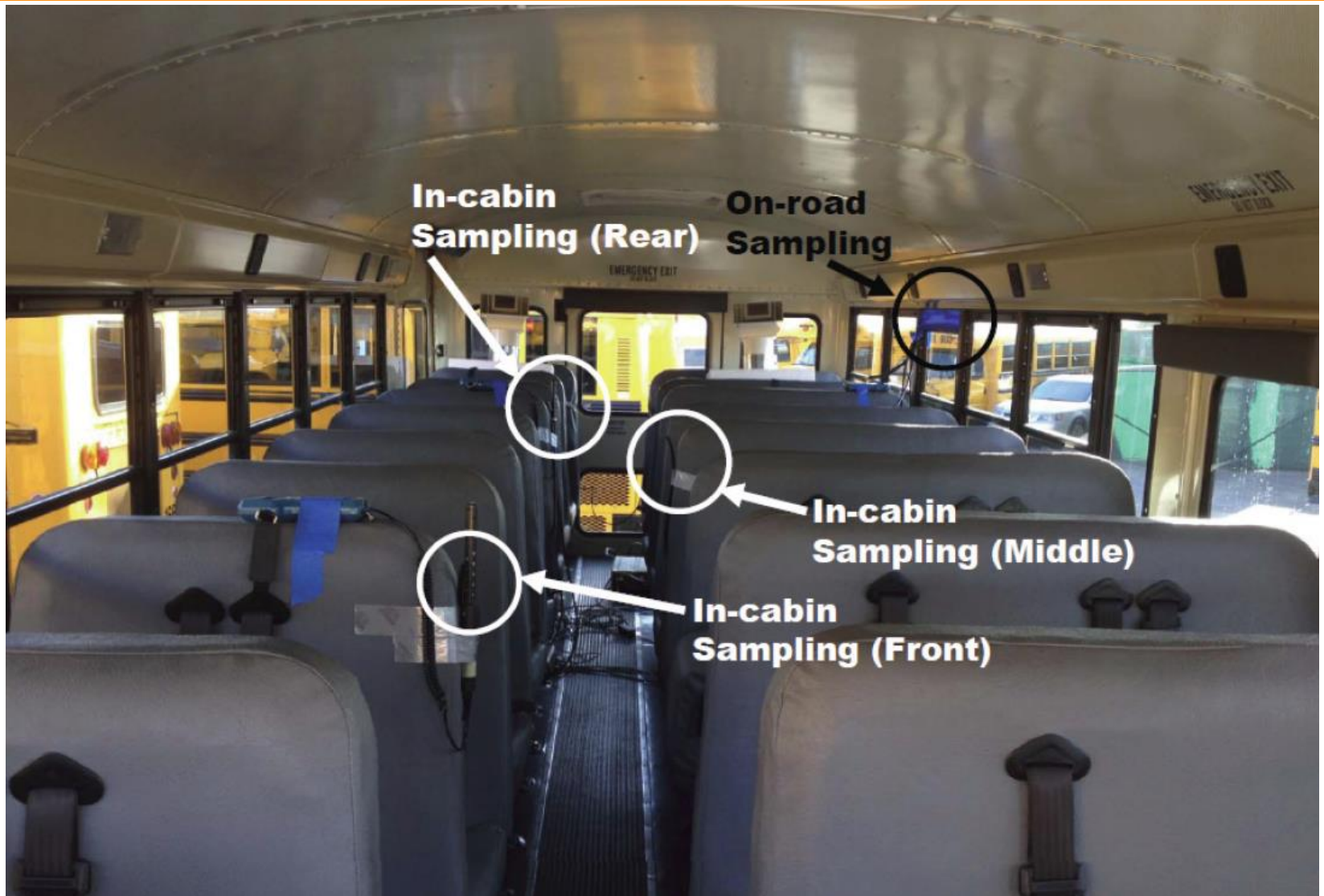
Experimental Set-up

- Six school buses
- With and without operating on-board HECA filtration system
- Three driving conditions: Stationary, Local, and Freeway
- Measurements: Ultrafine Particles, Black Carbon, and PM_{2.5}

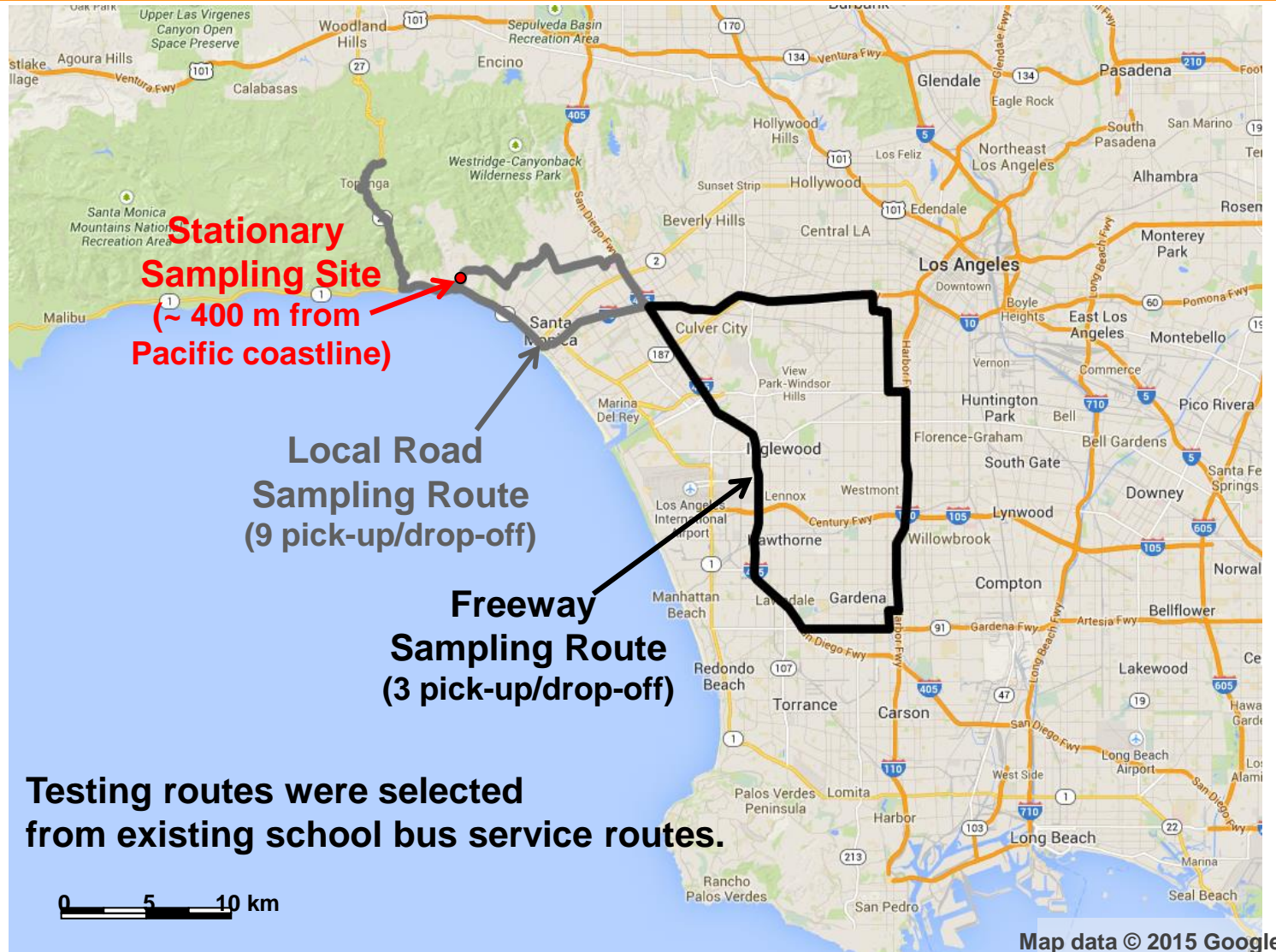
| Test Bus ID | School Bus Maker | Year | Passenger Capacity | Internal Volume (m ³) | Fuel Type | Engine Location | Exhaust Location |
|-------------|------------------|------|--------------------|-----------------------------------|-----------|-----------------|------------------|
| A | Thomas | 2006 | 22 | 22.3 | Diesel | Front | Rear Right |
| B | International | 2007 | 42 | 35.9 | Diesel | Front | Rear Left |
| C | Bluebird | 2013 | 48 | 32.3 | Propane | Front | Side Left |
| D | International | 2007 | 63 | 53.8 | Diesel | Rear | Side Left |
| E | Bluebird | 2010 | 78 | 52.4 | CNG | Rear | Rear Left |
| F | Thomas | 2011 | 80 | 50.6 | Diesel | Rear | Rear Left |

Note that all diesel school buses were equipped with diesel particulate filters.

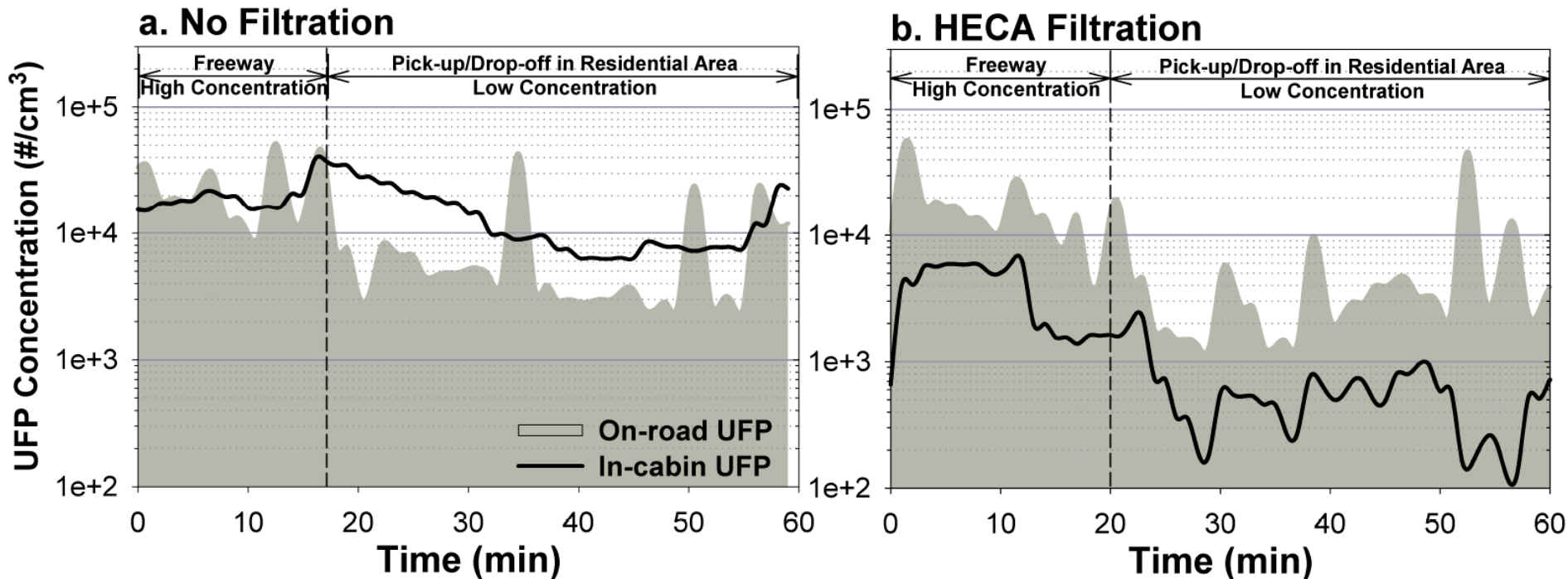
Instrument Set-up



Testing Routes

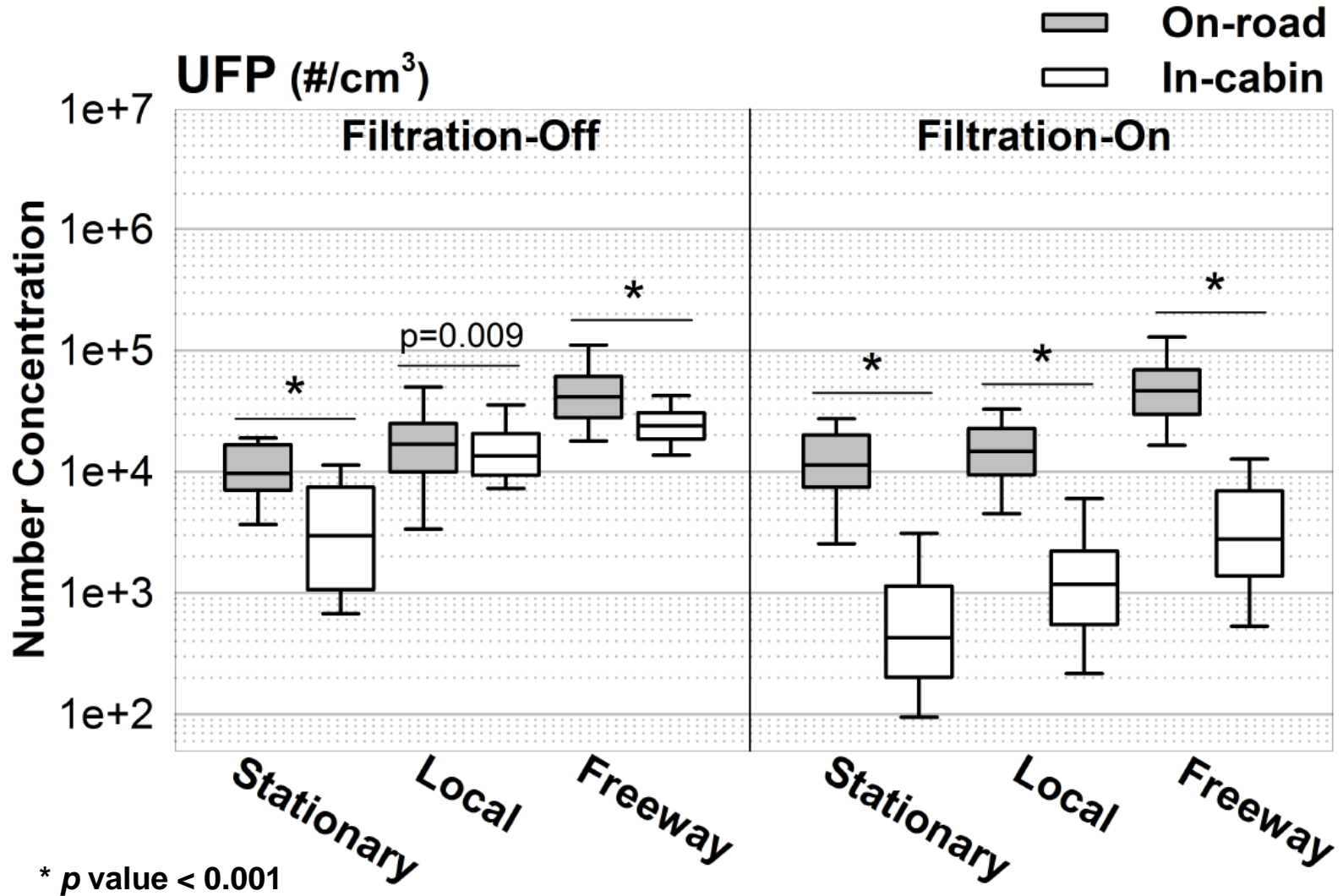


In-cabin vs. On-road Ultrafine Particle Concentrations

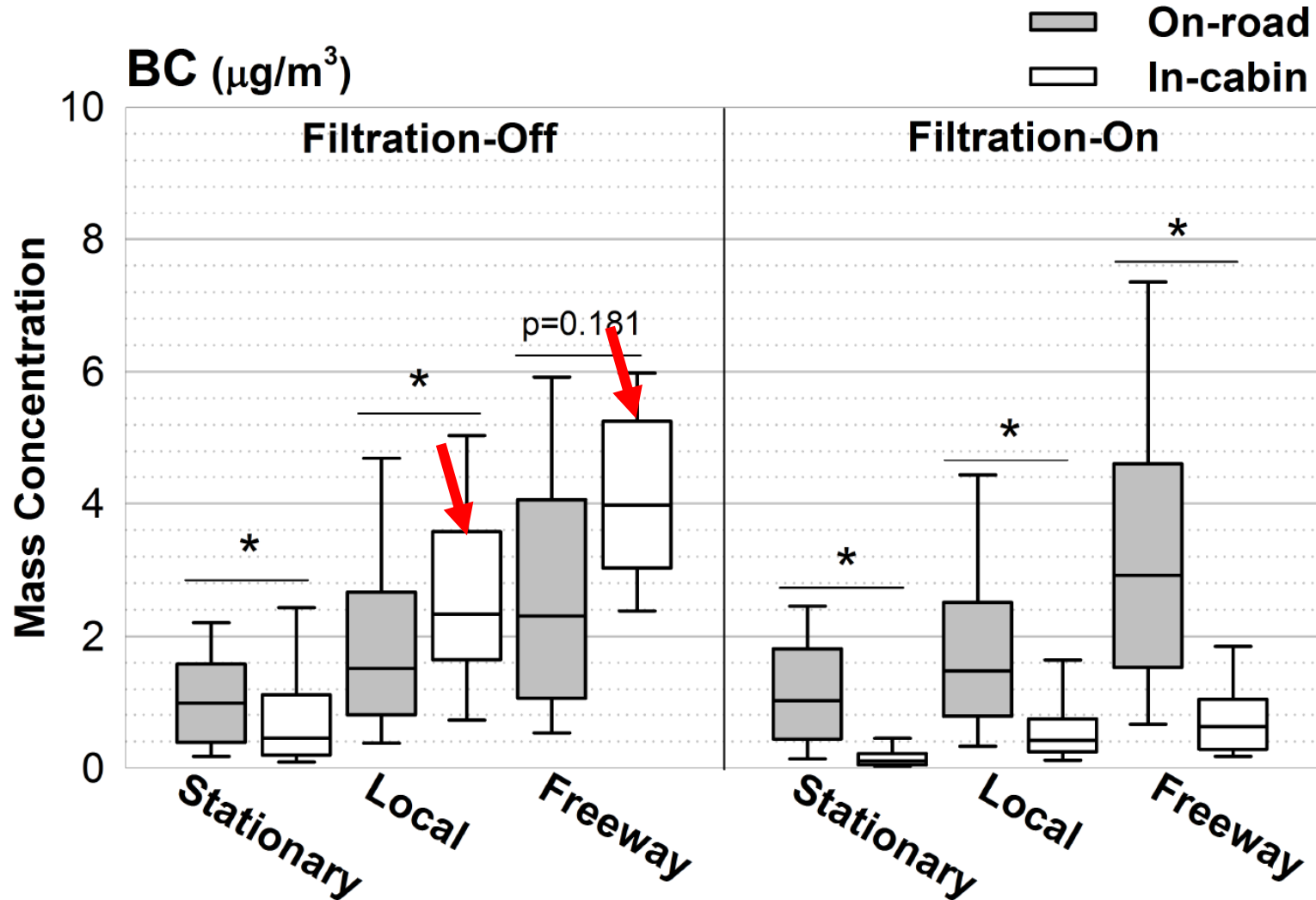


High UFP concentrations remained inside a large bus when the bus was driven from a freeway to a residential area.

In-cabin Exposure Reduction Ultrafine Particles

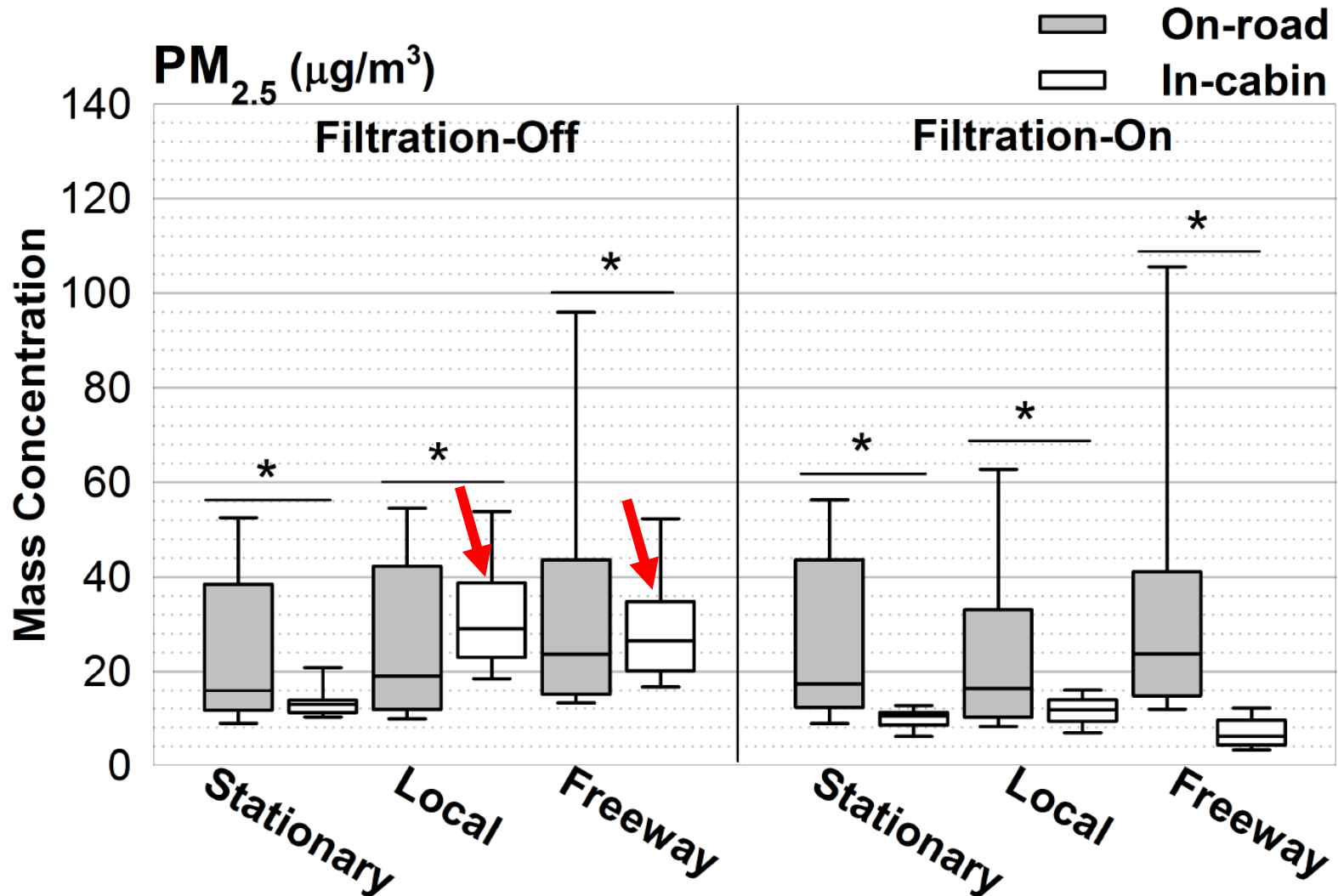


In-cabin Exposure Reduction Black Carbon

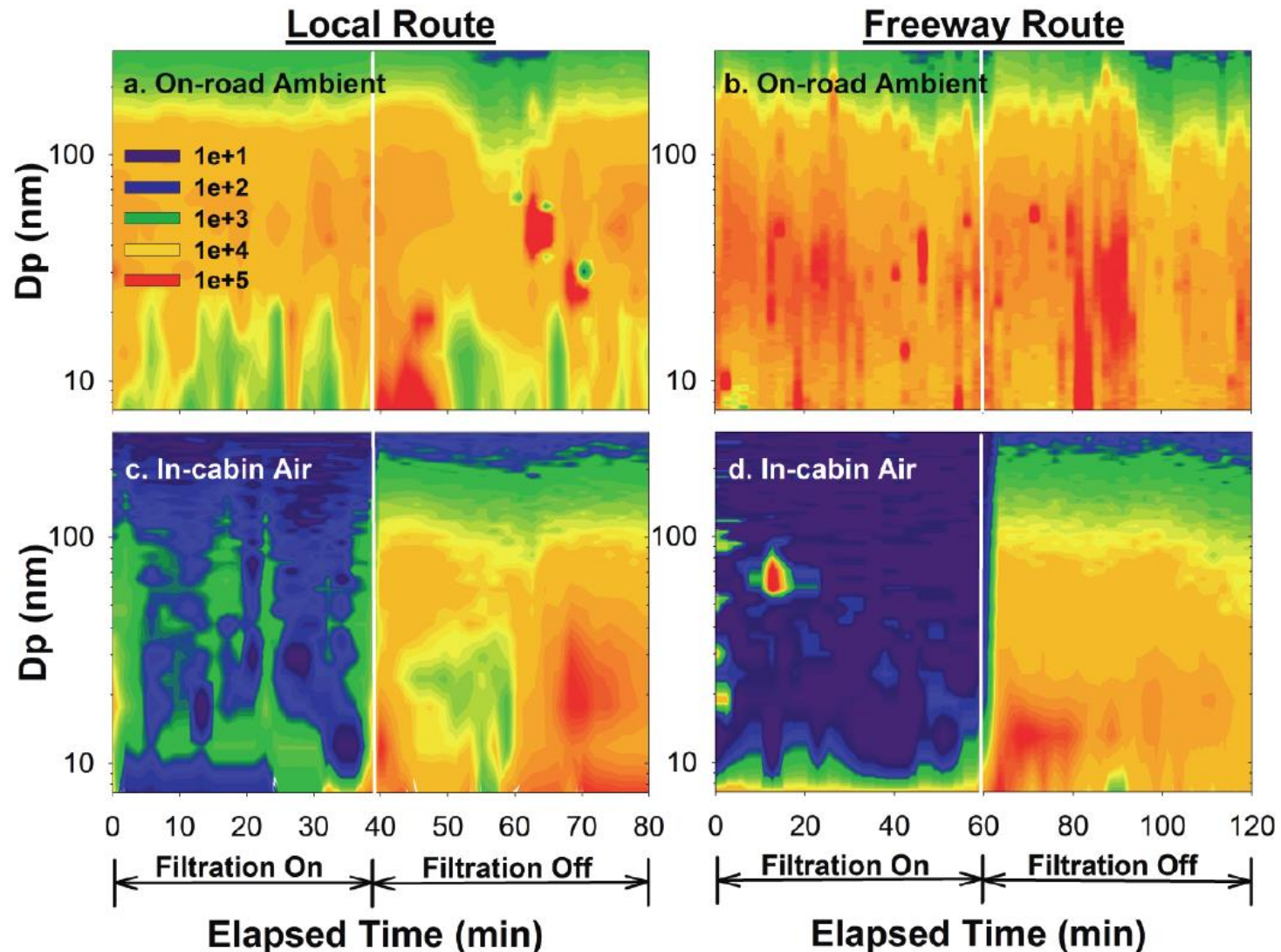


In-cabin Exposure Reduction

PM_{2.5}



In-cabin Exposure Reduction Temporal Changes



I/O Ratio Reductions

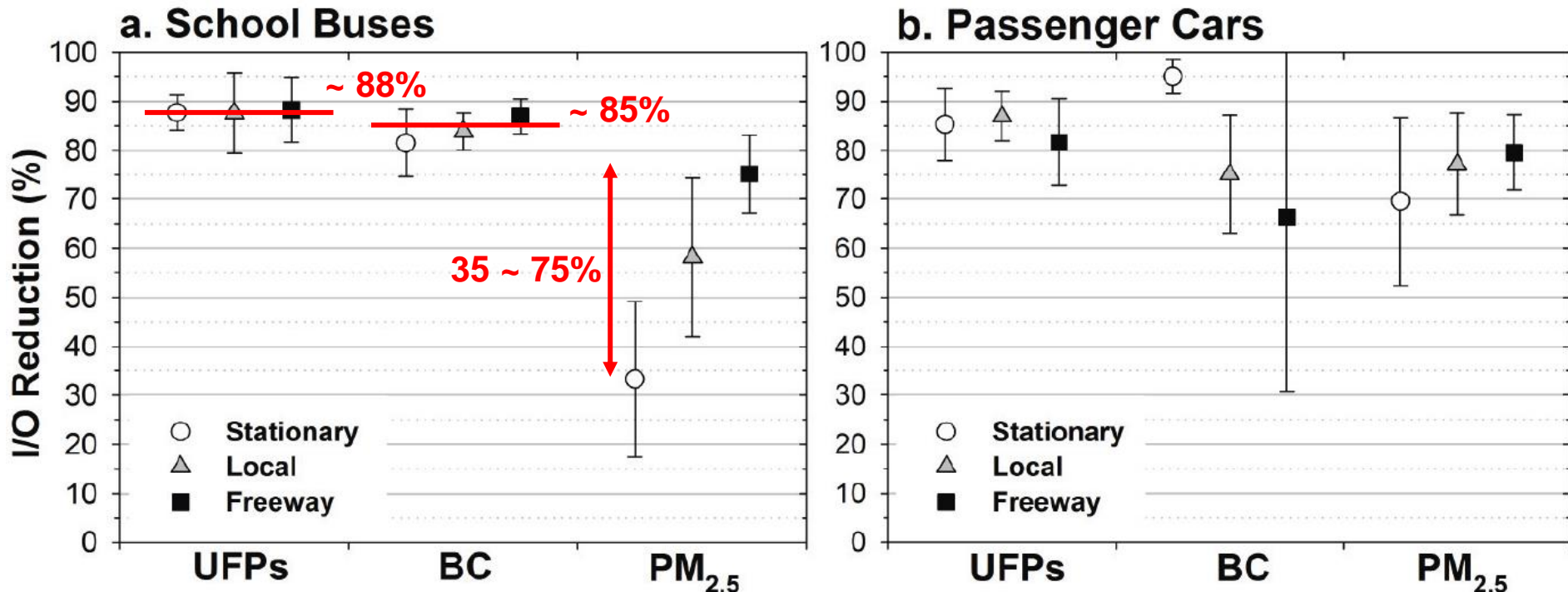
Used **I/O ratio reductions** due to self-pollution.

$$\text{I/O Reduction} = \left\{ 1 - \frac{(I/O)_{\text{HECA-on}}}{(I/O)_{\text{HECA-off}}} \right\} \cdot 100$$

where

$(I/O)_{\text{HECA-on}}$: I/O ratio with operating the on-board HECA system

$(I/O)_{\text{HECA-off}}$: I/O ratio without operating the on-board HECA system



Phase 2. Summary

- The developed on-board HECA filtration system reduced in-cabin UFP and BC I/O ratios by ~ **88%** and **85%**, respectively, in field conditions.
- The system reduced $\text{PM}_{2.5}$ I/O ratio by 35 ~ 75%, but maintained $\text{PM}_{2.5}$ level **below 12 $\mu\text{g}/\text{m}^3$** in school buses.
- Operating the HECA filtration system can **reduce children's exposures** regardless of pollution sources: on-road traffic pollution and self-pollution.

Limitation & Future Study

- The developed HECA filtration can become an effective exposure mitigation method in passenger cars and school buses.
- For passenger cars, the scope of this study is limited because only new HECA filters were tested.
- For school buses, a future study is needed with children on board because their activity might change the effectiveness of the HECA filtration system.
- Long-term evaluation is necessary to test
 1. Potential degradation of filtration efficiency in time
 2. Chronological development of pressure drop
 3. Window position and seasonal variables
 4. Potential CO₂ accumulation with children on board
 5. Fuel consumption when retrofitted with HECA filters

Acknowledgements

- We thank Tumbleweed Transportation and IQAir Inc. North America for collaboration.
- We thank Dr. David Fung, Dr. David Quiros, Claire Kim, and Nu Yu for the assistance in field sampling.
- We also thank Peggy Jenkins and Michael Gabor of the Research Division of the Air Resources Board for their inputs, review, and effective technical management of this project.
- This study is supported by
 - California Air Resources Board (ARB) under contract #11-310.
 - National Science Foundation (NSF) CAREER Award under contract #32525-A6010 AI.

Publications

Rectangular Snip

ENVIRONMENTAL
Science & Technology

Article

pubs.acs.org/est

Application of a High-Efficiency Cabin Air Filter for Simultaneous Mitigation of Ultrafine Particle and Carbon Dioxide Exposures Inside Passenger Vehicles

Eon S. Lee and Yifang Zhu*

Department of Environmental Health Sciences, Jonathan and Karin Fielding School of Public Health, University of California, Los Angeles, California 90095-1772, United States

ENVIRONMENTAL
Science & Technology


Article

pubs.acs.org/est

Evaluation of a High Efficiency Cabin Air (HECA) Filtration System for Reducing Particulate Pollutants Inside School Buses

Eon S. Lee, Cha-Chen D. Fung, and Yifang Zhu*

Department of Environmental Health Sciences, Jonathan and Karin Fielding School of Public Health, University of California, Los Angeles, California 90095-1772 United States

 Supporting Information

References

- Zhu, Y.F., Eiguren-Fernandez, A., Hinds, W.C. and Miguel, A.H. (2007) In-cabin commuter exposure to ultrafine particles on Los Angeles freeways, *Environmental Science & Technology*, 41, 2138-2145.
- Morawska, L., Ristovski, Z., Jayaratne, E.R., Keogh, D.U. and Ling, X. (2008) Ambient nano and ultrafine particles from motor vehicle emissions: characteristics, ambient processing and implications on human exposure, *Atmospheric Environment*, 42, 8113-8138.
- Fruin, S., Westerdahl, D., Sax, T., Sioutas, C. and Fine, P.M. (2008) Measurements and predictors of on-road ultrafine particle concentrations and associated pollutants in Los Angeles, *Atmospheric Environment*, 42, 207-219.
- Satish, U., Mendell, M.J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S. and Fisk, W.J. (2012) Is CO₂ an indoor pollutant? Direct effects of low-to-moderate CO₂ concentrations on human decision-making performance, *Environmental Health Perspectives*, 120, 1671-1677.
- Gauderman, W.J., Urman, R., Avol, E., Berhane, K., McConnell, R., Rappaport, E., Chang, R., Lurmann, F. and Gilliland, F. (2015) Association of improved air quality with lung development in children, *New England Journal of Medicine*, 372, 905-913.
- Behrentz, E., Fitz, D.R., Pankratz, D.V., Sabin, L.D., Colome, S.D., Fruin, S.A. and Winer, A.M. (2004) Measuring self-pollution in school buses using a tracer gas technique, *Atmospheric Environment*, 38, 3735-3746.
- Rim, D., Siegel, J., Spinhirne, J., Webb, A. and McDonald-Buller, E. (2008) Characteristics of cabin air quality in school buses in central Texas, *Atmospheric Environment*, 42, 6453-6464.
- Ireson, R.G., Ondov, J.M., Zielinska, B., Weaver, C.S., Easter, M.D., Lawson, D.R., Hesterberg, T.W., Davey, M.E. and Liu, L.J.S. (2011) Measuring in-cabin school bus tailpipe and crankcase PM_{2.5}: A new dual tracer method, *Journal of the Air & Waste Management Association*, 61, 494-503.
- Zhang, Q.F. and Zhu, Y.F. (2011) Performance of school bus retrofit systems: Ultrafine particles and other vehicular pollutants, *Environmental Science & Technology*, 45, 6475-6482.
- Marshall, J.D. and Behrentz, E. (2005) Vehicle self-pollution intake fraction: Children's exposure to school bus emissions, *Environmental Science & Technology*, 39, 2559-2563.
- Lee, E.S. and Zhu, Y.F. (2014) Application of a high-efficiency cabin air filter for simultaneous mitigation of ultrafine particle and carbon dioxide exposures inside passenger vehicles, *Environmental Science & Technology*, 48, 2328-2335.
- Lee, E.S., Fung, C.C.D. and Zhu, Y. (2015) Evaluation of a high efficiency cabin air (HECA) filtration system for reducing particulate pollutants inside school buses, *Environmental Science & Technology*, 49, 3358-3365.

Thank you!

